

FIELD OF THE INVENTION

The invention relates to the testing of semiconductor wafers during manufacturing and specifically to the real-time in-line testing of semiconductor wafers during integrated circuit fabrication.

BACKGROUND OF THE INVENTION

There are numerous individual operations, or processing steps, performed, in a strictly followed sequence, on the silicon wafer in the course of manufacturing a complex integrated circuit (IC). Each such operation must be precisely controlled in order to assure that the entire fabrication process yields integrated circuits displaying the required electrical characteristics.

Frequently, failure of an individual operation is detected only after the completion of the entire, very expensive, process of IC fabrication. Due to the very high cost of advanced IC fabrication processes, such failures result in the severe financial losses to the integrated circuit manufacturer. Therefore detection of errors in the manufacturing process, immediately after their occurrence, could prevent the unnecessary continuation of the fabrication of devices which are destined to malfunction, and hence, could substantially reduce the financial losses resulting from such errors.

Process monitoring in semiconductor device manufacturing relies upon the examination of the changes which occur in certain physical and/or chemical properties of the silicon wafer upon which the semiconductor devices are fabricated. These changes may occur

1 following the various processing steps to which the silicon wafer
2 is subjected and are reflected by changes in the electrical
3 properties of the wafer. Therefore, by monitoring selected
4 electrical properties of the silicon wafer in the course of IC
5 fabrication, an effective control over the manufacturing process
6 can be accomplished.

7 Not all of the electrical characteristics of a completed
8 integrated circuit can be predicted based on the measurements
9 performed on a partially processed wafer. Most of the
10 characteristics however, can be predicted directly or indirectly
11 based on the investigation of the condition of the surface of the
12 silicon wafer (substrate) in the course of IC manufacture. The
13 condition of the silicon surface is very sensitive to the outcome
14 of the individual processing steps which are applied during IC
15 manufacturing, and hence, the measurement of the electrical
16 properties of the substrate surface can be an effective tool by
17 which the monitoring of the outcome of the individual processing
18 steps can be accomplished.

19 The determination of the electrical characteristics of the
20 wafer surface typically requires physical contact with the wafer
21 surface, or the placement of a contactless probe over a stationary
22 wafer. In the latter case an optical signal or a high electric
23 field is used to disturb equilibrium distribution of the electrons
24 in the surface and near-surface region of semiconductor.
25 Typically, the degree of departure from equilibrium is driven by
26 variations of one or more electrical characteristics of the surface
27 region, the near-surface region, and the bulk of the semiconductor.

1 To obtain a more complete picture of the entire surface of the
2 wafer, several measurements at various points on the surface can be
3 made. Such a procedure, known as "mapping", moves the measuring
4 probe with respect to the measured material (or vice versa) over
5 the surface of specimen, stopping at a number of locations and
6 performing a measurement at each location before moving to the next
7 location. The substrate, in this procedure, does not remain in the
8 continuous motion, so consequently the applicability of such a
9 method for use in real-time in-line process monitoring is limited.

10 SUMMARY OF THE INVENTION

11 The invention relates to an apparatus and method for the real-
12 time, in-line monitoring of semiconductor wafer processing. In one
13 embodiment the apparatus includes a probe assembly located within
14 a semiconductor wafer processing line. As each wafer is carried
15 beneath or above the probe assembly by conveyor belt, robotic arm,
16 wafer chuck, or other similar device, a source of modulated light,
17 such as an LED, within the probe assembly, generates light having
18 a predetermined wavelength and frequency of modulation which then
19 impinges upon the wafer. A sensor in the probe assembly measures
20 the surface photovoltage induced by the modulated light. The
21 signal from the sensor is sent to a computer which then uses the
22 induced surface photovoltage to determine various electrical
23 characteristics of the wafer, such as surface charge and surface
24 doping concentration, among others.

1 BRIEF DESCRIPTION OF THE DRAWINGS

2 This invention is pointed out with particularity in the
3 appended claims. The above and further advantages of this
4 invention may be better understood by referring to the following
5 description taken in conjunction with the accompanying drawings, in
6 which:

7 Fig. 1 is a block diagram of an embodiment of an apparatus for
8 the real-time, in-line, electrical characterization of a
9 semiconductor during manufacturing;

10 Fig. 2 is a perspective view of an embodiment of the probe
11 assembly of the apparatus of Fig. 1 in position above a wafer
12 transfer system;

13 Fig. 3 is a top perspective cutaway view of the probe assembly
14 of Fig. 2;

15 Fig. 4 is a bottom perspective view of an embodiment of the
16 sensor plate of the probe assembly of Fig. 3;

17 Fig. 5 is a schematic diagram of an embodiment of an
18 electrical circuit for measuring the surface photovoltage using
19 front wafer surface coupling;

20 Fig. 6a depicts a block diagram of a corona control circuit
21 used to charge a wafer so as to generate an inversion layer at the
22 wafer surface; Fig. 6b depicts a block diagram of the corona
23 control circuit of Fig. 6a used to discharge a wafer;

24 Fig. 7 is a bottom perspective cutaway view of an embodiment
25 of the coated sensor plate of Fig. 4 with a polyimide coating, used
26 with sensor charging and high voltage biasing;

1 Fig. 8 is a schematic diagram of an embodiment of a
2 preamplifier circuit used for the high voltage biasing of the wafer
3 using the sensor electrodes; and

4 Fig. 9 is a graph of front and back surface charge
5 measurements of a silicon wafer undergoing cleaning.

6 DESCRIPTION OF THE PREFERRED EMBODIMENT

7 In one embodiment, the apparatus to perform various electrical
8 characterizations makes use of the method for measuring the photo-
9 induced voltage at the surface of semiconductor materials, termed
10 the surface photovoltage (SPV), disclosed in the U.S. Patent
11 No. 4,544,887. In this method, a beam of light is directed at a
12 region of the surface of a specimen of semiconductor material and
13 the photo-induced change in electrical potential at the surface is
14 measured. The wavelength of the illuminating light beam is
15 selected to be shorter than the wavelength of light corresponding
16 to the energy gap of the semiconductor material undergoing testing.
17 The intensity of the light beam is modulated, with both the
18 intensity of the light and the frequency of modulation being
19 selected such that the resulting AC component of the induced
20 photovoltage is directly proportional to the intensity of light and
21 inversely proportional to the frequency of modulation.

22 When measured under these conditions, the AC component of the
23 surface photovoltage (SPV), designated δV_s , is proportional to the
24 reciprocal of the semiconductor space-charge capacitance, C_{sc} . When
25 the surface of the specimen is illuminated uniformly, the
26 relationship between the surface photovoltage (SPV) and the space-

1 charge capacitance is given, at sufficiently high frequencies of
2 light modulation, by the relation;

$$\delta V_s = \frac{\Phi(1-R)}{Kf} q C_{sc}^{-1}$$

3 where Φ is the incident photon flux, R is the reflection
4 coefficient of the semiconductor specimen, f is the frequency at
5 which the light is modulated, and q is the elementary charge. The
6 constant K is equal to 4 for a square wave modulation of the light
7 intensity and is equal to 2π for sinusoidal modulation.

8 In the above referenced patent, only a uniform configuration
9 is considered in which the area of the sensor is at least the same
10 size as the semiconductor wafer and the entire area of the specimen
11 is uniformly illuminated. When only a portion of the semiconductor
12 specimen surface is coupled to the sensor, that is, when the sensor
13 is smaller than the wafer, and when the semiconductor surface
14 uniformly illuminated in that area is coupled to the sensor, the
15 surface photovoltage, δV_s , may be determined from the measured
16 signal, δV_m , according to the relationships :

$$\text{Re}(\delta V_s) = \text{Re}(\delta V_m) \cdot (1 + C_L/C_p) + \text{Im}(\delta V_m) \cdot (\omega \cdot C_p \cdot R_L)^{-1}$$

$$\text{Im}(\delta V_s) = \text{Im}(\delta V_m) \cdot (1 + C_L/C_p) - \text{Re}(\delta V_m) \cdot (\omega \cdot C_p \cdot R_L)^{-1}$$

19 where $\text{Re}(\delta V_s)$ and $\text{Im}(\delta V)$ are the real and imaginary components
20 of the voltage, ω is an angular frequency of light modulation, C_p
21 is the capacitance between sensor and the wafer, and C_L and R_L are
22 the input capacitance and resistance, respectively, of the
23 electronic detection system.

1 From the sign of the imaginary component, the conductivity
2 type may be determined. If the measurement is calibrated for a p-
3 type material, then the sign of the imaginary component will change
4 if the material is n-type.

5 Using above relationships, the depletion layer width, W_d , is
6 given by equation:

$$W_d = \frac{\epsilon}{q} \frac{\omega |Im(\delta V_s)|}{\phi(1-R)} \cdot (1 + [\frac{Re(\delta V_s)}{Im(\delta V_s)}]^2)$$

7 where $\phi(1-R)$ is the intensity of light absorbed in the
8 semiconductor, q is the elementary charge, and ϵ_s is the
9 semiconductor permittivity.

10 In addition to the space-charge capacitance, C_{sc} , the
11 measurement of the surface photovoltage can be used to determine
12 the surface charge density, Q_{ss} , the doping concentration, N_{sc} , and
13 the surface recombination lifetime, τ , using the following
14 relationships. The space charge capacitance, C_{sc} , is proportional
15 to the reciprocal of the semiconductor depletion layer width, W_d ,
16 according to the relationship:

$$C_{sc} = \frac{\epsilon_s}{W_d}$$

17 where ϵ_s is the semiconductor permittivity. The density of
18 space charge, Q_{sc} , is in turn described by equation:

$$Q_{sc} = q N_{sc} W_d$$

1 where q is an elementary charge and the net doping
2 concentration in the space-charge region, N_{sc} , is positive in an n-
3 type material and negative in a p-type material. In addition,
4 since the surface charge density, Q_{ss} , is given by the expression:

$$Q_{sc} = - Q_{ss}$$

6 the surface charge density is easily determined from the space
7 charge density.

8 Further, if an inversion layer can be created at the wafer
9 surface, the depletion layer width, W_d , under inversion conditions
10 is related to the net doping concentration, N_{sc} , according to the
11 relationship:

$$W_d = \sqrt{\frac{4\epsilon_s kT \ln(|N_{sc}|/n_i)}{q^2 |N_{sc}|}}$$

12 where kT is the thermal energy and n_i is the intrinsic
13 concentration of free carriers in the semiconductor. Several
14 methods of forming such an inversion layer at the semiconductor
15 surface are disclosed below.

16 Finally, the surface recombination rate may also be determined
17 from the SPV. The recombination lifetime of the minority carriers
18 at the surface, τ , is given by the expression:

$$\frac{1}{\omega\tau} = \left| \frac{Re(\delta V_g)}{Im(\delta V_g)} \right|$$

1 In brief overview, and referring to Fig. 1, an embodiment of
2 such an apparatus 10 for the real-time, in-line, electrical
3 characterization of a semiconductor during manufacturing using
4 induced surface photovoltage includes a sensor ~~probe~~ ^{head} assembly 14,
5 supporting electronics 18, and a wafer conveying device 22. In
6 operation, the wafer conveying device 22, such as a conveyor belt,
7 a robotic arm, a wafer chuck or similar device, moves wafers 28,
8 28' through the manufacturing process and, in one embodiment,
9 beneath the sensor head assembly 14.

10 Referring to Fig. 2, the sensor ~~probe~~ ^{head} assembly 14
11 includes a probe head 32 mounted in a bracket 36 on a motorized
12 stage 40. The motorized stage 40 moves the probe head 32 in a
13 vertical direction (arrow z) to adjust vertical position of the
14 probe head 32 with respect to the wafer 28 to within a 0.2 μ m
15 accuracy. The mechanical stage 40 is ~~attached to a probe arm 44.~~

16 The longitudinal axis L-L' of the probe head 32 is adjusted to
17 be perpendicular to the plane of the wafer 28, by adjusting the
18 tilt of the probe arm 44, either manually (using set screws 46) or
19 mechanically (using for example piezoelectric actuators 48). The
20 vertical position of the probe head 32 with respect to the wafer 28
21 is controlled by feedback signal from capacitive-position sensing
22 electrodes described in detail below.

23 Briefly, three capacitive-position sensing electrodes are
24 located on the periphery of the sensor. To measure capacitance
25 between each of these electrodes and the wafer, a 70 kHz 1V signal
26 is applied through a respective 10 kohm resistor connected to each
27 of these electrodes. The AC current flowing through these

1 resistors in measured using a preamplifier and a lock-in amplifier.
2 The lock-in signal is further processed by a computer and supplied
3 to the motion control board that, in turn, positions the probe at
4 a predetermined distance from the wafer surface using vertical (z-
5 axis) motorized stage.

6 Referring to Fig. 3, the probe head 32 includes a sensor mount
7 assembly 50 which provides support for a sensor 54 that is
8 connected to a preamplifier board 58 by a plurality of flexible
9 connectors 60. Light emitted by a light emitting diode (LED) 64 is
10 collimated by lens 68 prior to passing through a beam splitter 72.

11 LED 64 is mounted on a LED driver board 74 which controls the
12 intensity of the LED 64, in response to a signal from a reference
13 photodiode 78, (through a preamplifier 79) at an intensity level
14 determined by the computer 160. Light from the LED 64 reaches the
15 reference photodiode 78 by being partially reflected by the beam
16 splitter 72. The light which passes through the beam splitter 72
17 passes through openings 80, 82 in the circuit board 86 and the
18 preamplifier board 58, respectively, prior to passing through the
19 sensor mount assembly 50 and impinging on the wafer 28 undergoing
20 testing.

21 Light reflected by the wafer 28 passes back along the light
22 path just described before being reflected by the beam splitter 72
23 to a measuring photodiode 92. The light reflected by the wafer 28,
24 Φ_R , is used to detect edge of the wafer passing beneath the probe
25 head 32 and trigger measurements. The reflected light is also used
26 to measure light absorbed in the wafer 28 according to the
27 relationship:

1
$$\Phi = \Phi_0 - \Phi_R$$

2 where Φ_0 is the incident light which can be determined by
3 measuring the light reflected from an aluminum mirror replacing
4 the wafer 28. In this way, the reflection coefficient of the
5 wafer 28 can be determined. Although the above embodiment
6 describes the splitting of light by a beam splitter, other
7 embodiments are possible in which light is split using optical
8 fibers.

9 Referring again to Fig. 1, the LED 64 is controlled by signals
10 from, and the probe head 32 returns signals to, supporting
11 electronics 18. The supporting electronics 18 include an
12 oscillator 100 which supplies a 40 kHz modulation control
13 signal 104 that is used as a reference signal by an LED control 62
14 to control an LED driver 63 which powers the LED 64. Oscillator
15 100 also provides a reference signal 108 to a lock-in amplifier
16 112. The output signals 116 from the surface photovoltage sensor
17 and the measurement photodiode 92 (through a preamplifier 93) of
18 the probe head 32 are input signals to multiplexer 120 that
19 alternately connects each signal to the input of the lock-in
20 amplifier 112. The lock-in amplifier 112 demodulates the input
21 signal and supplies the demodulated signal to another multiplexer
22 150. Multiplexer 150 switches between the two input signals from
23 lock-in amplifiers 112 and 140 connecting them to a data
24 acquisition (DAQ) board 156 that in turn digitizes the input
25 signals making them available for further processing in the
26 computer 160. In an alternate embodiment, multiplexer 150 is part
27 of the data acquisition board 156.

Fig. 4 is a bottom perspective view showing the sensor plate of the sensor head 32. A plurality of electrodes are formed on a rigid and insulating substrate 200. In one embodiment, a 10mm diameter fused quartz disc is used. A central surface photovoltage electrode 204 detects the signal from the wafer 28. The central surface photovoltage electrode 204 is partially transmissive, thereby permitting the light from the LED 64 to reach the wafer 28. Three other electrodes 208 located on the periphery of the substrate are used both for sensing the position of the sensor head 32 above the wafer 28 and for measuring the parallelism of the sensor with respect to the surface of the wafer 28. All electrodes 204, 208 are formed by the deposition of an indium-tin-oxide film through a shadow mask.

Similarly, a plurality of electrodes 212, for connecting the sensors with the preamplifier circuit board 58 through the flexible connectors 60, are formed on the surface of the substrate 200 which is opposite the electrodes 204, 208. Thin conductive electrodes 218, on the side walls of the substrate 200, which connect the electrodes 204, 208 on the first surface with their respective electrodes 212 on the second surface, are also deposited using a shadow mask. This deposition avoids the use of vias through the substrate and thereby retains the flatness of the sensor to better than $.2\mu\text{m}$. Both front 204, 208 and side electrodes 218, may be protected with a thin insulating coating, such as polyimide, formed by spinning so as to maintain the flatness of the sensor.

The electrodes 208 are used for capacitively sensing the position of the sensor above the wafer 28. Referring again to

Fig. 1, a 70 kHz input signal 124 for measuring the distance from a wafer 28 is supplied by an oscillator 128 to the position electrodes 208. The same signal is also supplied as a reference signal 132 for a lock-in amplifier 140. A position signal 146 from each of the three position sensing electrodes 208 is supplied as the input signal to a multiplexer 148 through a preamplifier 149. The multiplexer 148 in turn, switching between each of these signals, connects each alternately to a lock-in amplifier 140. The demodulated output signals from the lock-in amplifiers 112 and 140 are input signals to a multiplexer 150 which connects each signal alternately to a data acquisition board 156 located in a computer 160, including a CPU 164. Again, in an alternative embodiment, multiplexer 150 is part of the data acquisition board 156.

The position signal 146 is compared by the CPU 164 with the reference value corresponding to a desired distance (established by calibration and stored in the computer) between the sensor 54 and the wafer 28. The difference between these two values, corresponds to the deviation of the sensor-wafer distance from the desired value, is supplied to a motion control board 170 that positions the probe head 32 at a predetermined distance from the wafer 28 using the motorized stage 40.

In operation, when an edge of the continuously moving wafer 28 crosses the beam of the intensity modulated light from LED 64, the intensity of the reflected light increases, thereby increasing the signal from the photodiode 92. This measurement of the reflected light is repeated and the new value compared with the previous

1 value. The light intensity measurements are repeated until the
2 difference between sequential values decreases to below 5%
3 indicating that the entire light beam is within the flat portion of
4 the wafer.

5 This decrease in deviation triggers acquisition of the SPV
6 signal by the surface photovoltage electrode 204, followed by
7 acquisition of the capacitance signals by the position
8 electrodes 208. If capacitance signals from different electrodes
9 (208) differ by more than 5%, the SPV signal is stored but not
10 recalculated. The sequence of all measurements is then repeated
11 until capacitances from different position electrodes (208) fall
12 within 5% limit indicating that the electrodes are not near the
13 edge of the wafer 28. The average of the capacitances from the
14 three positioning electrodes 208 at this point is used to
15 recalculate all previous values of the SPV signal.

16 The SPV measurement cycle is repeated, sequentially measuring
17 light intensity, SPV signal and capacitance of positioning
18 electrodes, until capacitances from the three positioning
19 electrodes (208) differ by more than 5%, indicating the approach of
20 the opposite edge of the wafer 28. After reaching this point of
21 the wafer 28, the SPV measurements are made using the previously
22 measured values of capacitance. The measurements of each value
23 (reflected light, SPV signal, capacitance), in each cycle, are
24 repeated for 10 msec and averaged by CPU 164.

25 The wafer 28, in one embodiment, is placed on the grounded
26 chuck (conveyor belt, robotic arm, or other similar device) 178,
27 coated with an insulating material, that is used to carry the

1 wafer 28 beneath, above, or otherwise, such that the surface of the
2 sensor of the probe head 32 and the surface of the wafer are
3 parallel. Alternatively, the conveying device may be biased by a
4 DC voltage. In one embodiment the DC bias voltage is selected to
5 be between -1000 and 1000 volts. Although Fig. 1 illustrates the
6 use of a grounded, insulated chuck 22 to move the wafer 28 beneath
7 the probe assembly 14, it is possible to provide all the necessary
8 measurements without grounding the chuck using only the electrodes
9 provided by the sensor 54. Referring to Fig. 5, the SPV signal is,
10 as described previously, received by the central surface
11 photovoltage electrode 204 which is connected to the input terminal
12 of an operational amplifier 250 located on the preamplifier circuit
13 board 58. The other input terminal of the operational
14 amplifier 250 is connected to ground and to the output terminal of
15 the operational amplifier 250 through one or more resistors. What
16 was previously a back capacitive contact, supplied by the chuck, is
17 now provided by the three positioning electrodes 208 located on the
18 periphery of the sensor and which, during the SPV measurements, are
19 connected to the ground 252 rather than to the input terminal of
20 the capacitance (current measuring) preamplifier located on the
21 preamplifier circuit board 58.

22 To measure capacitance, the electrodes 208 are alternatively
23 switched between the ground 252 and input of the capacitance
24 preamplifier located on preamplifier circuit board 58. This
25 arrangement makes possible non-contact measurements with any type
26 of wafer support. Thus, the wafer support does not need to be
27 connected to ground and could be made of insulating material.

1 As discussed above, measurements of the surface doping
2 concentration require the formation of an inversion layer at the
3 wafer surface. In one embodiment this is accomplished by charging
4 the wafer 28 using a corona generator and subsequently performing
5 surface photovoltage measurement on the wafer 28. Specifically,
6 the wafer 28 is first charged to inversion with a corona generator.
7 N-type wafers require a negative surface charge and p-type wafers
8 require a positive surface charge. In one embodiment, the corona
9 generator includes a single metal tip, for example tungsten,
10 located 5mm above the wafer 28 and biased to 3.5kV for 2 to 3 sec.
11 After charging, the wafer 28 is moved beneath the probe assembly 14
12 and the measurements performed. After the measurement, the
13 wafer 28 is either moved beneath a neutral charge corona generator
14 or returned to the original corona generator operated in a neutral
15 discharge mode in order to discharge the wafer.

16 The simple corona generator with the metal tip or wire does
17 not allow for the controlled charging of the wafer surface. The
18 control of charging is important because while there is a minimum
19 charge required to induce an inversion layer at the wafer 28
20 surface, overcharging may damage the wafer surface, and even cause
21 electrical breakdown of the insulating coating formed on the wafer
22 surface. To avoid overcharging the wafer 28, a closed loop
23 controlled corona charging arrangement, disclosed in Figs. 6a and
24 6b, controls the charge deposited on the surface of the wafer and
25 thereby prevents surface damage.

26 Referring to Fig. 6a, the wafer 28 on the grounded, insulated
27 chuck 22 is moved beneath an ionized air source 260 located about

1 10mm above the wafer 28. A mesh, stainless-steel, reference
2 electrode 264 is placed in a distance of about 0.5 mm to 1mm from
3 the wafer 28. The difference between the potential on the
4 reference electrode 264, V_{el} , and a user defined and computer
5 generated reference voltage, V_{ref} , 268, termed the differential
6 potential, V_{diff} , is amplified and its polarity is reversed within the
7 corona control module 270. This voltage, V_{corr} , is applied to the
8 ionized air source 260. Thus, the polarity of the potential
9 applied to the ionized air source 260, V_{corr} , by the corona control
10 module 270 is opposite to the polarity of differential voltage and
11 is given by the expression:

$$V_{corr} = V_{ref} - V_{el}$$

13 Control of the corona charging during the charging process
14 allows not only for real-time control but allows also simpler
15 electronic circuitry to be used. The presence of the ions between
16 ionized air source 260, reference electrode 264, and the wafer 28
17 lowers the equivalent impedances in the circuitry and permits
18 amplifiers to be used (in the control module 270) which have an
19 input impedance of $10^9 - 10^{10}$ ohms. This input impedance is several
20 orders of magnitude lower than in the amplifiers utilized in
21 previous approaches (typically $10^{13} - 10^{15}$ ohms) when a potential of
22 the wafer surface is measured not during charging but after the
23 turning off of the corona.

24 Referring to Fig. 6b, the wafer 28 may be discharged by
25 setting the reference voltage 268 to zero, i.e., connecting it to
26 ground. Alternatively, if separate corona units are used for

1 charging and discharging of the wafers, the discharging corona
2 reference voltage can be permanently attached to the ground.

3 Referring to Fig. 7, an alternative approach to inducing a
4 surface inversion layer is to bias the sensor with a high voltage.
5 Such an approach requires formation of the insulating film 230 such
6 as polyimide over the central electrode 204 and positioning
7 electrodes 208 of the sensor. Fig. 8 depicts this alternative
8 approach to inducing an inversion layer at the surface of the wafer
9 28 by voltage biasing. Fig 8 shows a schematic diagram of an
10 electronic circuit that includes a preamplifier for measuring AC
11 surface photovoltage and a connection to a biasing high voltage
12 source used with the sensor having a polyimide coating 230 as just
13 described. The insulating coating 230 of the sensor 54 allows the
14 application of a high enough voltage (500-1000 V) to induce a
15 surface inversion layer in typical wafers used in manufacturing.
16 The arrangement in which a rigid sensor electrode 204 is separated
17 by an air gap from the semiconductor surface requires high degree
18 of flatness of the electrode surface. When such a high DC voltage
19 is used, any edges or surface roughness will increase the local
20 electrical field and enhance ionization of the air resulting in
21 electrical breakdown. Therefore electrical connections between the
22 electrode and the detection electronics are constructed so as to
23 have a minimal effect on the surface flatness. Thus, the use of
24 the side connections 218 eliminates the need to form via holes in
25 the sensor and maintains the high flatness of the sensor. The
26 current in the space charge region of the wafer 28 (indicated in
27 phantom) which is generated by the illumination of the wafer 28 by

1 the LED 64 is depicted as an equivalent current source, J_h . An
2 equivalent resistor, R_R , which represents the carrier
3 recombination at the surface of the wafer 28 and an equivalent
4 capacitor, C_{SC} , which represents the space charge capacitance are
5 also depicted. C_G represents capacitance between the wafer 28 and
6 the chuck 22, while C_p represents capacitance between the sensor
7 electrode 204 and the wafer 28. A computer controllable high
8 voltage 300 is applied through a 10 Mohm resistor, R_{HV} , to the
9 sensor electrode 204. The sensor electrode 204 is also connected
10 to the input of the operational amplifier 250 (described
11 previously) through a high voltage capacitor, C_{HV} . The capacitance,
12 C_{OA} , (also shown in phantom) represents input capacitance of the
13 operational amplifier 250. C_{HV} is selected to be about 10 times
14 larger than C_{OA} so that C_L used in calculating $\text{Im}(\delta V_s)$ and $\text{Re}(\delta V_s)$ is
15 close to C_{OA} . Similarly R_L used in calculating $\text{Im}(\delta V_s)$ and $\text{Re}(\delta V_s)$
16 is close to R_{HV} .

17 In addition to the methods just described to form an inversion
18 layer, an inversion layer at the surface of the wafer 28 can be
19 also formed using a chemical treatment. This approach is
20 especially useful for p-type silicon wafers. Since HF introduces
21 positive surface charge, HF treatment will produce a negative
22 inversion layer at the surface of p-type silicon wafers. In one
23 embodiment, the silicon wafer to be tested is subjected to a
24 mixture of hydrofluoric acid and water (1:100 HF:H₂O) in a liquid
25 or vapor form. The wafer is then placed beneath the probe
26 assembly 14. In number of processes, HF treatment is already part

1 of the production sequence so that probe assembly 14 needs only to
2 be placed after HF processing location.

3 It should be noted that the formation of an inversion layer is
4 useful in measuring conductivity type.

5 Since, in some cases, incoming wafers show acceptor
6 neutralization due to the presence of hydrogen or copper, in order
7 to restore the doping concentration at the surface, the measured
8 wafer is subjected to a high intensity illumination (e.g., using a
9 250W halogen light source) after a SPV measurement is made.

10 Additionally, the present apparatus is particularly adaptable
11 for use in a sealed chamber environment, such as a reduced pressure
12 chamber, a chamber for chemically reactive gasses or a chamber for
13 an inert environment. The entire probe assembly 14 may be
14 positioned within the sealed chamber, with the connections to the
15 electronics passing through the walls of the sealed chamber through
16 pressure fittings. Alternatively, the probe assembly may be
17 mounted in a wall of a sealed chamber such that the sensor is
18 positioned within the chamber but the remainder of the probe
19 assembly is positioned outside of the sealed chamber.

20 The approach to process monitoring methodology using an AC-SPV
21 method emphasizes determination of variations of the measured
22 parameters from wafer to wafer rather than value of the specific
23 parameter itself. Typically, measurements of the electrical
24 parameters of the back surface of the wafer are not possible
25 without altering the front surface, which has to be contacted in
26 order to complete a measuring circuit. Hence, measurements
27 performed on the back surface of the wafer are not typically used

1 in process monitoring. The non-contact AC-SPV measurements allows
2 process monitoring by measurement of the surface characteristics on
3 the back surface of the wafer as well as the front surface. As
4 described before, the probe head can be installed underneath the
5 wafer, above the wafer, or otherwise, such that the sensor surface
6 is parallel to the wafer back surface, depending on how the wafer
7 conveying system conveys the wafer to the probe head. In addition,
8 two probe heads can be used, one on each side of the wafer for
9 simultaneous characterization of the front and back side of the
10 wafer. As an illustration of such approach comparison of
11 measurements of the surface charge on the front surface featuring
12 mirror-like finish is shown in Fig. 9. The measurements were
13 performed on the two halves of the same 100mm, p-type, (100)
14 silicon wafers that were simultaneously subjected to the wet
15 cleaning treatments. At various stages of the cleaning process,
16 the surface charge was measured on the front (polished) surface of
17 one half, and on the back (unpolished) surface of the other half.
18 The results shown in Fig. 9 indicate identical behavior of surface
19 charge on the front and back surfaces.

20 Having shown the preferred embodiment, those skilled in the
21 art will realize many variations are possible which will still be
22 within the scope and spirit of the claimed invention. Therefore,
23 it is the intention to limit the invention only as indicated by the
24 scope of the following claims.